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by

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DEVELOPMENT OF FOREIGN HIGH-POWERED MICROWAVE WEAPONS AND PROSPECTS OF FUTURE APPLICATIONS IN SPACE-BASED TARGET DEFENSE AND AIR DEFENSE

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Abstract: This paper outlines the development of foreign high-power microwave weapons and their technologies and, by introducing high-power microwave sources and effects, analyzes the prospects of their applications in space-based target defense and air defense.

Key Words: 1. microwave weapons; 2. microwave sources; 3. microwave effects.

1. Introduction [1-5]

There are usually two types of microwave weapons, i.e., those generating monopulses from nose cone explosion energy, and repetition-frequency devices that can produce multipulses. By comparison, the first type of microwave weapons was found to be realized in practice earlier. The "Tomahawk" cruise missile, as a new experimental nonnuclear electromagnetic pulse nose cone, launched by the U.S. Navy during the Gulf War, can be classified in this category. It was primarily used to destroy the Iraqi electronic network, including their air defense weaponry and command and control center. During this military confrontation, the nose cone converted energy from ordinary dynamite into radio-frequency energy pulses which the, through antennas, conducting

wires, or other metal connecting wires, penetrated the opponent's computer-aided weapons to cripple the network. The electromagnetic pulses could damage or even break down the electronic systems, on the assumption that the pulse power was high enough and that the electronic components inside enemy weapons had not been hardened. In the Gulf War, it was not easy to discriminate the damage effect of F-117 stealth aircraft bombing, missile attacks, as well as the constant electronic jamming. One is convinced, however, that the weapon mentioned above played its part in paralyzing the Iraqi air defense system. The former Soviet Union, though inferior to the United States in capacitor technology, is capable of producing energy and electric current levels ten times more than the United States can. The former Soviet Union can generate 100MJ of microwave energy in a single transmission. Furthermore, Soviet scientists have used an approximately "desk-size" explosion generator which, upon being installed in a weapon, can convert explosion energy into an intensive electric power pulse. Currently, the U.K. Ministry of Defense is conducting research aimed at developing "microwave bomb" technology. This kind of bomb is based on a hollow traveling-wave tube, where the radio-frequency standing waves resonate at a fixed frequency. When an explosive is detonated at one end of the tube and then damages it, the blast generates an amplified radio-frequency pulse. This reaction process can provide a pulse with a duration of about 2ps and a power of 1GW. To develop the "microwave" technology, a knotty problem lies in how to keep the transmission of the explosive force moving along the traveling-wave tube at the same speed as the pulse speed.

The second type of microwave weapon, which can be used over again, is what is generally referred to as a high-power microwave weapon. This is the main topic of this paper. By using a transmitting antenna, a high-power microwave weapon can attack targets through convergence of high-power microwaves into a very narrow beam. The high-power microwaves are defined as microwave

radiation at a wavelength varying from 30cm to 1mm (frequency from 1 to 300GHz) and a power level exceeding 1GW. The "Strategic Defense Initiative" (SDI) carried out for ten years by the United States and the "Space Defense Program" conducted by the former Soviet Union had both been supported with a large contingent of manpower and heavy funding in order to develop directed-energy weapons. Compared with laser and particle beam weapons, the high-power microwave weapon shows its strength with features such as wider beam, longer operating range, and less effects from weather and smoke.

Radar electronic interferometers differ from microwave weapons in radiation power. Unlike conventional weapons, usually called a "hard killer", the electronic interferometer acts like a "soft killer", whereas high-power microwave weapons can generate interference when its power is rather low and a destructive force when its power is rather high, i.e., it can function either as both an electronic interferometer and a conventional weapon, or it can execute both "hard killing" and "soft killing" against targets.

High-power microwave weapons research and testing still continue in the United States, Russia, and other foreign countries. In view of its technological level, even though it is too early to apply this weapon in defense against space-based targets, it still can be used in low-altitude and particularly minimum-altitude air defense.

2. Highlights of Microwave Weapons Development [6-9]

It was early in World War II that some British radar experts came up with an idea of developing a "super-interferometer", which could transmit microwaves intense enough to destroy enemy electronic networks, i.e., the high-power microwave weapon. Since then, however, this weapon long remained at the stage of

conceptual demonstration. It was not until the high-power microwave source technology (the essence of the weapon) had continuously developed that realization of the concept could gradually become possible. High-power microwave sources were developed on the basis of ordinary microwaves and especially, the advances made in relativistic-effect electron beam technology. In the sixties there first appeared the carcinotron, a new device based on the relativistic effect, which was followed by the relativistic-effect backward-wave oscillator, the relativistic magnetron, the free electron laser, and the imaginary negative pole oscillator developed in the seventies, the circular acceleration self-resonance-stimulated radiation microwave amplifier, the relativistic traveling-wave tube, and the relative velocity-regulating tube in the eighties, and the Cerenkov multiwave generator and the relativistic diffraction generator in the nineties. The emergence of these sophisticated high-power microwave sources laid the groundwork for the successful development of high-power microwave weapons.

In the seventies, the United States initiated a research program involving the kill mechanism of high-power microwave weapons and high-power microwave sources, which was given even greater attention in the eighties. In 1984, the U.S. Defense Department included this weapon category in the SDI directed-energy weapons program and further, designated it as one of the 22 priority military-oriented technologies in the Fiscal Year 1990 Key Technologies Program. Later, in Fiscal Year 1992 Key Technologies Program, the Defense Department set a clear goal aimed at providing the different applications of high-power microwave weapons and other interferometers with microwave sources of relativistic character with extra-peak power. At the same time the timetable for the project development was scheduled as follows: produce 500J pulses and construct initial weapons and interferometers in the laboratory during Fiscal Year 1994-1995, and generate 1000J pulses and commence the development of high-

power microwave weapons and interferometers for specialized military missions in Fiscal Year 1996. Thus far, by using free electron lasers to derive energy from rather high voltages, scientists in the United States achieved success in generating high-power microwaves at the front end.

The United States recently canceled its SDI program against the Soviets but retained its research program on high-power microwave weapons. In fact, in the past few years, the U.S. Defense Department has focused growing interest on improving the conventional defensive posture of the nation and its allies; it took active part in implementing the "Balanced Technology Initiative" (BTI) and the "Conventional Defense Initiative" (CDI), and applied new SDI technology to conventional defense systems. For instance, the high-power microwave weapon is designated as one of the five top research areas in BTI with five specific requirements, which include high-power microwave sources, effects, transmission, hardening technology, and kill assessment method.

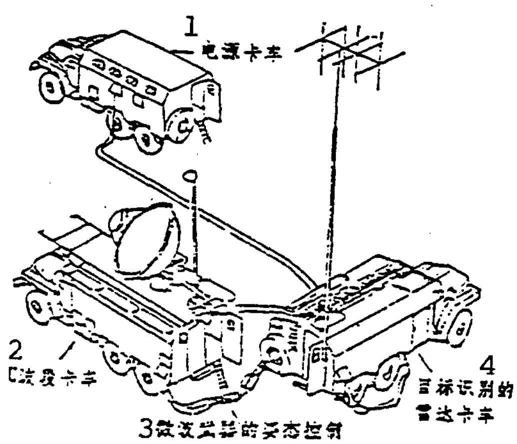

Fig. 1. Composition of Soviet air-defense microwave weapon system
KEY: 1 - power supplies truck 2 - U-waveband truck
3 - attitude control of microwave weapon
4 - radar truck for target identification

In the seventies, the Soviets embarked on using amplified radio-frequency signals to jam or destroy enemy weapons and planned a massive research program on high-power microwave technology, which has continued to the present. Unlike the United States, the former Soviet Union constantly shifted its focus so as to find newer and better ways of facilitating their research. Based on their achievements in research on pulsed power techniques related to high-power microwaves, Soviet scientists carried out a large-scale project on developing beam diodes specifically designed for high-power microwave research. By using a series of new devices (including the Cerenkov multiwave generator and the relativistic diffraction generator), they succeeded in producing microwave power that set a world record. Obviously, the former Soviet Union is already ahead of the United States in research on high-power microwave technology.

The Soviets conducted an air defense-oriented microwave weapon (see Fig. 1), which, designed for protecting their command center, could operate over a range of 1 to 10km. With a total weight of 13T, the system was loaded in three trucks. The first large truck held the power engine and fuel. The second truck, smaller in size, carried the microwave weapon, which was separated from the power supply to avoid being jammed. The third vehicle was loaded with an antiaircraft search radar. This weapon could radiate 1GW microwaves, which could attack a target with a power density of 400W/cm within 1km and 4W/cm at 10km. This system could reduce the efficiency of avionics equipment and aiming systems in the attacker, disable the normal functioning of antiradiation missiles, and prevent air-launched guided missiles from detonating normally.

Currently, Russia is conducting research on using high-power microwave weapons against ballistic missiles and satellites, as well as antisatellite testing with over-the-horizon high-power microwave weapons. In contrast, the United States is reacting

steadily and cautiously to the development of this weapon. For example, the investment that the U.S. administration makes in this weapon accounts for merely 1-2% of the budget on directed-energy weapons, which inevitably hinders its development. Nevertheless, this weapon has attracted attention in the U.S. Army, Navy, and Air Force; these services have, respectively, made investments in their research in line with their different technical requirements. The Army prefers a system small enough to be installed in a tracked vehicle, while the Air Force needs an "aerospace platform" system that is difficult to detect. As for the Navy, it requires a system with even higher power and longer range, regardless of its weight, size, and power that the Army and Air Force are particularly concerned with. In some ways, the Navy is likely to become the first service to deploy a high-power tactical microwave system with the capability of destroying microelectronic systems. Presently, a demonstration verification test is underway in the United States on a high-power microwave weapon dealing with targets. It is reported that it will take about $300 million to construct such a weapon system that can deprive aircraft of combat effectiveness. Hence the time schedule for official deployment and application of this weapon is subject to the level of investment made.

Thus far, apart from the United States and the former Soviet Union, who have already implemented the most comprehensive high-power microwave research projects, other countries such as France, Germany, Switzerland, and Japan are also wasting no time in following suit in this area.

3. Composition and Key Technologies in High-Power Microwave Weapons [10,11, 14, 15]

The major elements of this weapon category include pulse-power equipment, high-power microwave sources, antenna, and tracking, aiming, and control systems. The pulse-power equipment

generates extremely amplified electromagnetic pulses that drive the high-power microwave source, the heart of the weapon. The microwave energy outputted by the source converges, through an antenna, into a microwave beam that is greatly amplified to be directed at a target. Since this kind of research is regarded as highly classified in some countries, including the United States, there are few sources of information on this aspect. Thus, useful data can be obtained only from limited documents. As far as the tracking, aiming, and control systems are concerned, they are similar to those of other weapons and will not be further discussed in this paper.

3.1. Pulse-power Equipment

The rapid development of high-power microwave technology substantially relies on advances in other technologies. In the sixties, pulse-power generation technology developed swiftly in response to the need for nuclear weapon effect simulation. Later, this technology was further boosted by nuclear fusion research. The short, intensive electromagnetic pulses necessary for driving a high-power microwave load is derived from pulse compression, that is, the timewise compression of the energy outputted by a low-pressure, long-pulse system in order to increase the output voltage and output current at the expense of pulse duration. To improve the efficiency in transmitting the pulse energy toward the high-power microwave load, impedance matching is required.

Generally, there are three types of pulse-power equipment applied in a high-power microwave system. The first type of equipment utilizes a common capacitor bank to drive a pulse forming line (PFL). When connected to the load, it releases energy in its insulating medium at the speed of light. Two basic kinds of PFL are adopted in a high-power microwave system. The first PFL is charged directly from a Marx generator. A Marx

generator is a capacitor complex in which the capacitors are in parallel connection when charged and swiftly shift to series connection after the charge is expended. In this case, the voltage of the series-connected capacitors becomes the charging voltage multiplied by the number of capacitors. Through a high-pressure switch, this kind of PFL changes into a load. The second kind of PRL employs a capacitor bank at low voltage, as well as a changer, which can increase the voltage and charging pulse circuit. The superiority of this kind of PFL can be exhibited through its high-repetition frequency application. In the event that the repetition frequency exceeds 10Hz, the Marx generator can be ignored because it is vulnerable to greater losses and faults. CIS states and the U.S. Sandia National Laboratory are giving much attention to developing a changer application. As an example, the Tomsk Research Institute of High-Current Electronics developed an accelerator called Radan. With a compact structure, is changer can generate electric power of 150MW and drive a 10MW, 15GHz traveling-wave tube, together with a gain of 30dB when the repetition frequency reaches 10Hz.

The second type of pulse-power equipment applied in high-power microwave systems is a hysteresic memory device, which can provide an energy density two orders of magnitude higher compared with electrostatic memory device. However, this method has not been widely used due to some technical limitations.

The third type of pulse-power equipment is a linear induction accelerator (LIA) developed by the United States and by this CIS for particle accelerator applications in the eighties, as shown in Fig. 2. One feature of this equipment is that the required accelerating voltage is offered by several pulses as branch equipment and that electron beam takes place in vacuum. The LIA operates as a series of 1:1 pulse branch changers, each of which is passed through by electron beams. In the overall equipment the key device that makes the voltage accumulate is the

ferrite magnetic core in each acceleration cavity. Since the voltage can be increased by increasing the number of cavities, the overall equipment is basically a modular system. Even though the LIA system is rather expensive to use, it is still applicable since the number of compression factors that can be obtained at each level is up to 3 to 5, and the equipment is less bulky. The linear induction accelerator has now been used in driving free electron lasers, relativistic magnetrons, and relativistic velocity-regulation tubes.

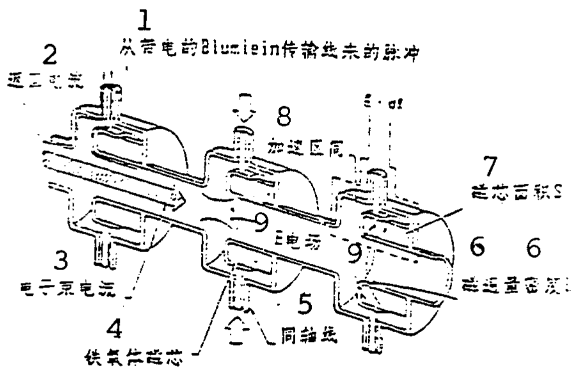

Fig. 2. Linear induction accelerator

KEY: 1 - pulse from charged Blumiein transmission line 2 - return electromagnetic wave 3 - electron beam current 4 - ferrite magnetic core 5 - coaxial line 6 - magnetic flux density 7 - area of magnetic core S 8 - acceleration interval 9 - electric field

3.2. High-power Microwave Sources [11, 14, 15]

As the heart of the high-power microwave weapon, high-power microwave sources are developed on the basis of ordinary microwave sources. When the operating frequency is increased to the microwave band, the output power and efficiency of the original devices based on the electrostatic control principle decrease dramatically because of the electronic transition effect. To overcome the harmful effect due to the electron delay, it is necessary to transform, in a sense beyond the

concept of electrostatic control, the kinetic energy obtained by the electron beam from the direct-current field to microwave energy constantly in a transition process. This kind of dynamic control method serves as a functional principle for all high-power microwave sources.

When studying various devices that can generate high-power microwaves, the United States and the former Soviet Union have engaged in a series of analyses of their efficiency, power, and effects, respectively. These devices usually emit pulses instead of continuous beams. Short pulses thus emitted are 50 to 100ns in typical cases and can even reach the mus level, in other

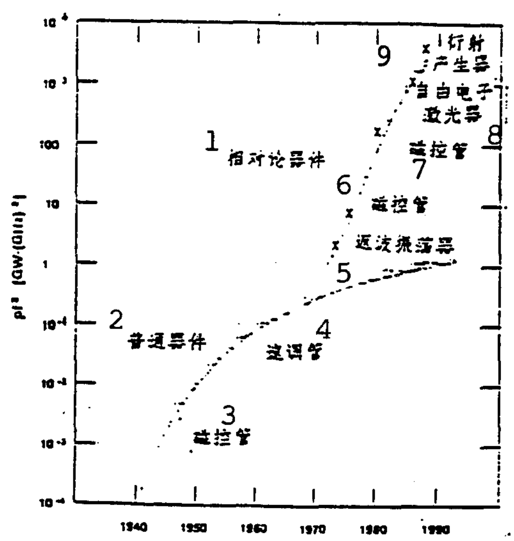

Fig. 3. Development of microwave sources demonstrated with Pf^2

KEY: 1 - relativistic device 2 - ordinary device 3 - magnetron 4 - velocity-regulation tube 5 - backward-wave tube 6 - magnetron 7 - magnetron 8 - free electron laser 9 - diffraction generator

cases. The working pattern of pulses is considered as the only way to emit microwaves with extremely high power and may provide

an efficiency of 10 to 12%, depending on the equipment used. The high-power microwave source under present research can provide sufficient power but narrower pulses and therefore, it is generally believed that with such limited total energy output, this source cannot be applied in weaponry. Thus, scientists are undertaking an in-depth study of different high-power microwave sources in the hope of developing equipment that can generate total energy in a single monopulse. Nevertheless, success has yet to be seen in their endeavor and much has to be done in the search for different ways to make the goal come to fruition.

High-power microwave source development can be evaluated with Pf^2, the square of source peak product (P) and signal frequency (f), because the power density of a fixed-level antenna-emitted microwave signal projected against a target is directly proportional to Pf^2. In Fig. 3 we can see that Pf^2 signifies the history of the microwave source development, during which ordinary microwave devices increased their power by three orders of magnitude from 1940 to 1970 but very little since then. In the following 20 years, relativistic devices began to increase by three orders of magnitude when Pf^2 reached 1. Fig. 4 shows the relationship between peak power and frequency of each typical microwave source, where the Pf^2 value is given in the form P/λ^2. The figure also indicates a tendency of a gradual drop in the peak power increase with frequency in the case of high frequency, but such change appears insignificant when frequency becomes lower than 10GHz.

High-power microwave source research has been conducted extensively in the United States. The U.S. Army Harry Diamond Laboratory is engaged in studying backward-wave oscillators, traveling-wave tubes, and imaginary negative pole oscillators, while the Naval Research Laboratory is concentrating its work on velocity-regulation tubes, carcinotrons, circular acceleration self-resonance-stimulated radiation microwave amplifiers, and

free electron lasers, and the Air Force Laboratory--on imaginary negative pole oscillators and some more recent devices. As for industrial laboratories, the International Physics, Inc., laboratory is focusing on development of imaginary negative pole oscillators, magnetrons, and velocity-regulation tubes. Varian, Inc., laboratory deals with carcinotrons and magnetrons, Mission Research, Inc., laboratory--on imaginary negative pole oscillators, the Energy Department's Lawrence Livermore National Laboratory--on free electron lasers, imaginary negative pole oscillators, and velocity-regulation tubes, and the Sandia National Laboratory--on backward-wave oscillators and some other newer devices. Among universities involved in this research, the Massachusetts Institute of Technology is working on carcinotrons, circular acceleration self-resonance-stimulated radiation microwave amplifiers, magnetrons, and free electron lasers, the University of Maryland--on carcinotrons, ring velocity-regulation tubes, backward-wave oscillators, and free electron lasers, Cornell University--on backward-wave oscillators and traveling-wave tubes, and the University of California--on circular acceleration self-resonance-stimulated radiation microwave amplifiers and carcinotrons.

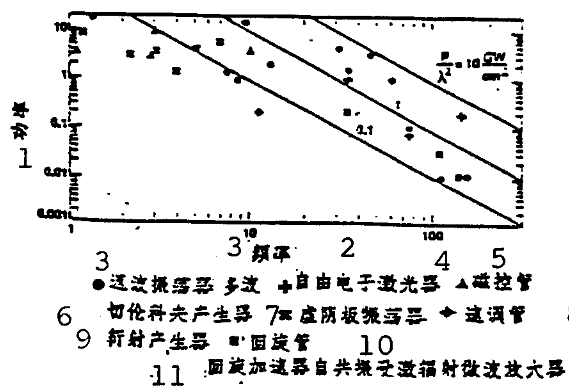

Fig. 4. Peak power of microwave sources
KEY: 1 - power 2 - frequency 3 - backward-wave oscillator multiwave 4 - free electron laser 5 - magnetron 6 - Cerenkov generator 7 - imaginary negative pole oscillator 8 - velocity-regulation tube 9 - diffraction generator 10 - carcinotron 11 - circular acceleration self-resonance-stimulated radiation microwave amplifier

Universities in the United States play an important role in these research projects. For example, in the University of Maryland this project is conducted under the direction of Dr. W. Destier, dean of the electronics department, who started his work on high-power microwaves, including relativistic backward-wave oscillators and some other devices in the mid-seventies. His research group made significant achievements, in collaboration with scientists at the U.S. Army Harry Diamond Laboratory, in building and studying the Cerenkov multiwave generator, which is similar to the backward-wave oscillator.

The United States made tremendous efforts and scored remarkable successes in high-power microwave source research, such as steadily strengthening the feature of carcinotrons used for plasma heating, studying some new microwave sources such as the quasioptical free electron laser, verifying the swinging cone in increasing the output power and efficiency of the free electron laser, upgrading magnetic switch technology necessary for producing reliable and long-lived electron beam accelerators, as well as exploring various phase-locking techniques. The U.S. research program of this kind is still underway. Scientists at the Naval Research Laboratory and the Air Force Weapons Laboratory are experimenting with a combination of several high-power magnetrons, anticipating the generation of high-power microwave radiation. The Power Spectra Company development of an in-body avalanche semiconductor switch claims the possibility of improving high-power microwave sources. This switch contains a gallium arsenide semiconductor chip, which when irradiated with a low-power laser, can, by causing the avalanche effect, be transformed from a nonconductive state into an excellent conductor capable of converting direct current into a microwave pulse signal. With an extremely high power density, the in-body avalanche semiconductor switch, when applied to future high-power microwave weapon systems, will greatly reduce system bulk and weight. Since 1989, the Power Spectra Company and the Boeing

Company have made considerable investments in changing the switch from laboratory equipment to an engineering prototype.

Ahead of the United States in high-power microwave research, the former Soviet Union has done tremendous work and paved the way for establishing its basic concepts. For example, the Soviets spent more than 20y specifically on the basic conceptual study of the backward-wave oscillator. With a single Cerenkov oscillator, Soviet scientists produced a maximum peak power of 15GW. The Gorkiy-based Applied Physics Research Institute and the Tomsk-based High-Current Electronics Research Institute are the two most active microwave research centers in the former Soviet Union. The Applied Physics Research Institute program focusses on the development of carcinotrons for large plasma heating experiments, as well as circular acceleration self-resonance-stimulated radiation microwave amplifiers, traveling-wave tubes, and magnetrons. The High-Current Electronics Research Institute, in cooperation with the Moscow Radio Engineering and Electronics Research Institute and Moscow University, set a world record in generating microwave power from several sources, including a backward-wave oscillator and a traveling-wave tube. In addition to the foregoing, the Nuclear Physics Research Institute of the Tomsk Polytechnic College is working on magnetrons and imaginary negative pole oscillators, Moscow General Physics Research Institute--on carcinotrons and plasma Cerenkov-stimulated radiation microwave amplifiers, Moscow University--on surface wave oscillators and microwave source theory, and some other institutions, including the Moscow Radio Engineering and Electronics Research Institute--on related theories. Among the major achievements the Soviet have made are the following: high average power produced by a Cerenkov multiwave generator, a multiwave diffraction generator, and a relativistic diffraction generator, development of several small microwave sources with high pulse repetition frequency, high peak power and high average power, development of output couplers,

including high-efficiency design for carcinotrons and a GW-class structure for a Cerenkov multiwave generator.

In Europe, Germany, France, and Switzerland have shown great interest in microwave source research, such as Valvo, Inc., and the Nuclear Research Center in Germany; Thomson-GSF, Inc., and the Atomic Energy Laboratory in France; and Brown-Boveri, Inc., and the Federal Polytechnic College in Switzerland. The focus of research in the European countries is on carcinotrons. France pays more attention to free electron lasers and dielectric Cerenkov-stimulated radiation microwave amplifiers. Japan has developed its interest in carcinotrons, velocity-regulation tubes, and free electron lasers.

3.3. Antennas

A high-power microwave system transmits its energy through antenna. The system, though equipped with an ordinary antenna, transmits microwaves at high power and in short pulse duration and therefore, the antenna must be adaptable to the high electric-field effect and short pulses in operation. In this case, antenna directivity becomes extremely important, that is, it must have the ability to concentrate microwave radiation power in a particular direction. The antenna radiation field can be subdivided into several regions. Take the electric field of a horn antenna, as an example. In the reacting near-field region, the electromagnetic field has not been completely separated from the transmitting antenna, next comes the radiation near-field, where the microwave beam takes on a cylindrical shape, varying in intensity and still further is the radiation far-field, that is, the microwave transmitting region.

When an antenna transmits microwaves, the core of the microwave beam is the major lobe, while directions deviating from the beam become the side lobes (due to diffraction) and leakage

radiation, and the direction opposite to the beam becomes the back lobe. These effects tend to be minor far from the antenna, but near the antenna become so powerful as to damage any electronic systems and personnel near the antenna, which fact should receive special attention.

When a high-power microwave system is applied to the atmosphere, the major point to be considered in antenna design is how to prevent a breakdown. If the local electric field of the antenna is fairly high, it may cause air ionization and St. Elmo's fire. Further, a continuous breakdown may form a conductive region where the electromagnetic waves will be reflected or absorbed so as to reduce antenna efficiency. Since breakdown is closely associated with air pressure intensity, the breakdown threshold value varies in light of the system application environments: ground-to-air or air-to-ground. In addition, the breakdown threshold value is also related to pulse duration, for example, pulses shorter than 1ns may not cause a breakdown.

At present, high-power microwave systems utilize horn antennas, formed in the open slot of the rectangular or circular waveguide extended by the high-power microwave source. The parabolic antenna, widely used in ordinary microwave applications, is required to avoid the formation of a high-power electric field when applied to the system. A slot antenna is also applicable to high-power microwave systems. Recently, antenna arrays have become a new option, which is very helpful in preventing breakdown as well as in rapidly tracking and attacking a target.

4. High-power Microwave Effect and Its Applications [10, 12, 15, 16]

The high-power microwave radiation effect has long since

attracted attention. Thus far, there have been several reports from foreign military publications covering military plane crashes due to the use of radar and communication transmitters. However, none of these reports is more shocking than the tragic event that befell the aircraft carrier U.S.S. Forrestal, on July 29, 1967. On that day, the Forrestal was just leaving the North Vietnam coast with a number of A-4 Skyhawk jet fighters on board. They had already completed over 700 missions. Now most of the fighters were refueling and each carried 500kg of bombs, air-to-air and air-to-surface missiles. As a cable screen joint on one missile was improperly fitted, it generated, when irradiated with a shipboard radar, a radio-frequency charge that detonated the missile and the missile struck another fighter. As a result, the fighter that was hit, together with the bombs and missiles on board, immediately exploded, causing a loss of 134 lives and $72 million in damage.

In terms of power, the high-power microwave effect can be broken down into three levels, in ascending order. The first level, higher than the power of battlefield-based jamming systems, resembles a kind of super-jamming system that can completely suppress enemy communication and radar systems. The second level can provide a power high enough to destroy microcircuitry in enemy electronic systems. The third level possesses a high power that can heat up a target like a household microwave oven. Naturally, high-power microwaves can hurt the human body to varying degrees, from burning skin and eyes to cause a body temperature rise and damaging the brain and the nervous system.

In the early eighties, the microwave transmitter effect was already verified in some U.S. research institutions. For example, a microwave beam emitted from a microwave transmitter could ignite steel wool 14m away and a mixture of gasoline, aluminum foil, and air 76m away, and could detonate a flashbulb

[illegible] away. Scientists at the U.S. Lawrence Livermore National Laboratory conducted a study on a variety of high-power microwave effects. The study involved aspects such as high-power microwave effect physics, effect of microwave power at different orders of magnitude on electronic equipment in various weapon systems, computational and simulation studies on the high-power microwave effect on military-oriented electronic equipment. In the research, they centered their efforts on determining, in terms of physics, how microwave power could penetrate into the weak point of a particular weapon system and jam or devastate its electronic components.

High-power microwaves can, through "front-gate" coupling, enter an electronic system as "back-gate" coupling. "Front-gate" coupling signifies the process of microwaves entering, via an antenna, a system containing a transmitter or receiver, while, "back-gate" coupling means that the microwaves enter the electronic system through open slots and gaps in its metal housing. "Front-gate" coupling is apt to destroy an electronic system because electronic devices most sensitive to microwaves are microwave detector diodes with a burnout threshold value of merely 1μJ. "Back-gate" coupling appears more complex, and its effect on an electronic system depends on factors such as the structure of the metal case, alignment of internal wires and cables, breakdown threshold values of devices and circuits, as well as the screen condition. Moreover, microwave energy in the amplifier or the digital circuits may increase owing to parasitic resonance, which leads to nonlinear response in the circuits and transmits in the system thereby disturbing normal data transmission and storage. In some cases, pulses or signals thus generated may damage parts of the system.

Lockup is defined as a state when semiconductor devices no longer respond to input. Remaining in the lockup state, the semiconductor devices cannot function and may even be damaged.

Generally, parasitic transistors may be formed in the manufacture of integrated circuits, forming PNPN or NPNP switches. This kind of switch can be triggered either by transient biassing and radiational ionization caused by microwave radiation on the parasitic PN junction, or an increase in charge carriers due to the heating effect. Once this switch is triggered, devices will lockup. Under the action of short pulses, the major failure mechanism of semiconductor devices is thermally-caused secondary breakdown. Thermally-caused secondary breakdown takes place when the PN junction region undergoes heating from microwave radiation. The appearance of thermally-caused secondary breakdown is associated with pulse duration and average power. Table 1 lists the destructive threshold power values measured from some conventional integrated circuits with a 100ns pulse duration.

At present, electronic equipment is provided with a great variety of sophisticated VLSI circuits, which, with submicron devices, close pulse frequency of 10MHz, and 3.3V logic levels, are highly sensitive to high-power microwave radiation. When irradiated with high-power microwaves, they display high vulnerability to disturbances and destruction. Under such conditions, microwave radiation incident on a minicomputer and a microcomputer with power density $10.6 mW/cm^2$ will be in disorder and sometimes even fail to work altogether. The higher the clock pulse frequency, the more vulnerable the computer will be to disturbances from microwave radiation.

The microwave effect is related to frequency and pulse duration, but power is still the most important factor. Table 2 shows the range of microwave power density within which ordinary facilities will be disturbed and destroyed. Based on the present-day technological level, Table 3 lists the maximum microwave flux, power density, and electric field intensity available along the aiming line over different distances, taking

as an example a microwave beam with microwave power 10GW, pulse duration 100ns, frequency 1GHz, parabolic antenna area 100m, and aperture efficiency 50%. It is noted, by comparing Table 2 and Table 3 that the high-power microwave weapons developed at the present-day technological standards can be used for air defense within the low-altitude short range (height 0.1 to 6km, range<30km), can jam electronic equipment on board aircraft or missiles over long distances, and can severely damage aircraft or missiles at minimum altitudes (height<100m).

When transmitted in the atmosphere, microwaves are greatly attenuated at some frequencies due to conditions such as absorption and scattering by air, vapor, and rain, and therefore, microwave weapon frequencies are selected to lie within the atmospheric windows. Since atmospheric debris causes a minor effect on microwave radiation, microwave weapons can maintain their power even in battlefields with poor visibility from heavy smoke, with which laser and particle-beam weapons are not comparable. Additionally, high-power microwave beams show high capability in acquisition of targets since the beams are rather wide and diverge little while being transmitted. Conversely, laser and particle-beam are too narrow to be aimed and thus extremely high precision is required in their operation. Obviously, high-power microwave weapons are very much suitable for use in low-altitude and particularly minimum-altitude air defense.

The Air Force Weapons Laboratory (AFWL) under the U.S. Air Force Space Technology Center (AFSTC) is working on high-power microwave weapon technology and its applications. For example, they are experimenting with a means against minimum-altitude enemy aircraft, that is, when enemy aircraft, taking advantage of terrain features, is covertly sweeping along the surface, high-power microwaves can be used to destroy its radar altimeter and force it to increase its altitude and then expose itself under

the air defense fire to be eventually downed.

TABLE 1. INTEGRATED-CIRCUIT DAMAGE RATE THRESHOLD VALUES (MEASURED VALUES)

1 器 件	2 类 型	3 失效功率(W)		
		4 输入引线	5 输出引线	6 电源引线
Fairchild 9930	双 4 输入门 7	730	290	660
Signetics SE 8481	四 2 输入与非门 8	230	149	1230
TI 946	四 2 输入与非门 9	50	60	870
Sylvania SG140	四 2 输入与非门 10	170	210	660
Motorola MC301G	5 输入门 11	2020	950	4400
Radiation Inc. 709R	运算放大器 12	50	57	206
Motorola MC1539G	运算放大器 13	890	15000	5400
TI 709L	运算放大器 14	1600	11000	8400
Radiation Inc. RD211	双 4 二极管门扩展器 15	63	63	-
Radiation Inc. RD220	六反相器 16	110	430	1080
Radiation Inc. RD221	双二进制门 17	850	570	2180
Radiation Inc. RA239	放大器 18	-	160	210
Philbrick Q25AH	混合放大器 19	630	50	1000
Philbrick Q25AM	混合放大器 20	320	6300	3200
Fairchild MA709	运算放大器 21	35	95	

[KEY on next page]

KEY: 1 - devices 2 - type 3 - failure power (W) 4 - input lead wire 5 - output lead wire 6 - power supply lead wire 7 - double 4-input gate 8 - four 2-input and negative gate 9 - four 2-input and negative gate 10 - four 2-input and negative gate 11 - 5-input gate 12 - operational amplifier 13 - operational amplifier 14 - operational amplifier 15 - double tetra-diode gate expander 16 - six inverter 17 - double binary gate 18 - amplifier 19 - mixer amplifier 20 - mixer amplifier 21 - operational amplifier

TABLE 2. POWER DENSITY NEEDED FOR DISTURBING AND DESTROYING MILITARY EQUIPMENT

1 设备和武器类型	2 作用方式	3 效应	4 功率密度 W/cm²
微波雷达、通信系统 5	从天线进入 6	干扰 7	10^{-8}:10^{-6}
传感器电子设备 8	吸收微波能量 9	干扰 10	0.01—0.1
传感器电子设备 11	感应微波电流淹没原有信号 12	停止工作 13	10—100
飞机、导弹 14	短时间内燃烧或引爆 15	加热破坏 16	10^{3}～10^{4}

KEY: 1 - types of equipment and weapons 2 - operating mode 3 - effects 4 - power density 5 - microwave radar, communication system 6 - enter through antenna 7 - disturbance 8 - sensor electronic equipment 9 - absorb microwave energy 10 - disturbance 11 - sensor electronic equipment 12 - inductive microwave current swamps original signal 13 - stops functioning 14 - aircraft, missile 15 - burn or detonate in a short period of time 16 - thermal destruction

TABLE 3. THREE PHYSICAL QUANTITIES ALONG 10CW, 100ns, 1GHz BEAM AIMING LINES

距离 1	通 量 2	功率密度 3	电场强度 4
100m	2.8mJ/cm²	56kW/cm²	4.6kV/cm
1km	28μJ/cm²	560W/cm²	460V/cm
5km	1.1μJ/cm²	22W/cm²	90V/cm
10km	0.28μJ/cm²	5.6W/cm²	46V/cm
32km	0.027μJ/cm²	0.5W/cm²	14V/cm

KEY: 1 - distance 2 - flux 3 - power density
4 - electric field intensity

The initial objective of developing high-power microwave weapons by the United States and the former Soviet Union was to apply them against space-based targets. Space-based targets include military satellites, space-based kinetic-energy weapon control platforms, space-based laser weapons, and so on. The Soviet research institutions managed to obtain valuable test results from utilizing high-power microwave beams to jam and destroy electronic equipment in satellites and missiles, which made the Soviet military force plan an over-the-horizon high-power microwave weapon antisatellite program. The United States, in contrast, pinpointed kinetic-energy and laser weapons in this area, setting aside any high-power microwave weapon program. Technically, high-power microwave weapons can, thus far, jam and destroy electronic equipment in space-based targets only over short distances. In other words, to develop these weapons into efficient anti-space-target weapons requires considerably

~~ing their transmitted power and also solving other relative problems. Owing to the dissolution of the Soviet Union, cancellation of the U.S. SDI Program and the increasing relaxation of the global situation, the possibility that high-power microwave weapons can be used against space-based targets is uncertain for a considerable period of time. Objectively speaking, Russia now intends to apply these weapons in air defense, while the United States--in naval ship defense.

Conclusions [6, 11, 13]

Since the eighties, both the United States SDI Program and the Soviet "Space Defense Program" have taken directed-energy weapons as their major concern. As high-tech advances are made, high-power microwave, laser, and particle-beam weapons have made rapid strides. The United States and the CIS have made remarkable headway in developing high-power microwave sources, the heart of high-power microwave weapons. In a matter of a few years, laboratory achievements will soon be transformed into the development of a practical weapon system. Table 4 summarizes the current level of high-power microwave sources and predicts the potential standard that it may arrive at by the end of this century.

Compared with microwave interferometers intended for use in electronic warfare, high-power microwave weapons have proven superior in efficiency as well as in function. This class of weapon can jam enemy radar, communication, and other systems over long distances, destroy electronic systems on enemy aircraft, warships, and armored vehicles over short distances, killing operators on board, shooting down aircraft and paralyzing armored vehicles. In other words, high-power microwave weapons can be brought into full play in future warfare as a new strategic weapon. Nevertheless, to become an anti-space-target weapon, it is necessary to improve its power substantially and also overcome

other technical obstacles, which will obviously take a relatively long time.

Prospects of High-power Microwave Weapon Development

a) In the early eighties, some countries, including the United States and the former Soviet Union speeded up their research on three directed-energy weapons: lasers, particle beams, and microwaves. The U.S. "SDI" Program at one time was concerned specifically with laser and particle beams. Subsequently, instead of the two, the fast-developing kinetic-energy weapon became a strategic alternative. Originally, the United States invested little manpower and funding in research on high-power microwave weapons. However, starting from the late eighties, it took more interest in this weapon than in lasers and particle beams. The former Soviet Union kept close attention on research into high-power microwave weapons and possessed a dynamic research staff and advanced technological level. Since the nineties, U.S. and CIS research on such weapons has been in full swing. The reason is that electronic war has become increasingly important in present-day warfare as fully demonstrated in the Gulf War. By the way, high-power microwave weapons in strategic application can virtually serve as a powerful weapon used in electronic war in future warfare. In view of the development of high-power microwave sources, their pulse power may reach 100GW by the turn of the century. If so, by then or in early next century, such powerful microwave weapons may soon be placed in use on the battlefield.

b) The former Soviet Union developed high-power microwave weapons with greater enthusiasm in an attempt to use them as an air defense weapon to counterattack aircraft and missiles, while the United States aims at defending its own warships, in the first place. In sort, both countries follow two guidelines: First, protect vital facilities or military equipment. Second,

strike high-value targets such as aircraft and missiles. This is primarily so because high-power microwave weapons are considered to be extremely efficient when applied in air defense and especially in low-altitude and minimum-altitude air defense. High-power beams, traveling at the speed of light, react swiftly to high-speed targets like aircraft and missiles. With a particular diameter, a microwave beam can be fired without aiming accurately. Over short distances, microwaves can produce even stronger energies to be employed in firing at random, and therefore can handle grouped aircraft and massive missiles. Microwaves can effectively strike targets by destroying the electronic equipment installed on aircraft and missiles.

c) In view of future warfare, it is vitally important to reduce weapon size and weight as to enhance mobility in operation. Recently, some foreign countries are experimenting with some new techniques, including superconducting magnets and plasma. For example, when an ordinary magnet is replaced with a superconducting magnet, the latter will not be heated and thus the enormous cooling system can be saved. Another example is the fact that the transformation efficiency of microwave energy can be largely increased if plasma is placed in a drift tube. All these measures will help decrease weapon size and weight. However, the most significant means is to reduce the size and weight of the microwave source occupying a large proportion of the weapon system. Yet this will take a long time to realize because at present the power capacity of solid microwave devices cannot match that of microwave electronic tubes. Hopefully, with new solid-state device technology, the concept of a solid-state microwave source may soon come to fruition. For example, some foreign countries are exploring a way of using a photoconductive changer to directly change light energy into microwave energy without using an electron beam. This not only will raise microwave energy efficiency, but also reduce the size and weight of high-power microwave sources.

TABLE 4. STATUS AND PREDICTIONS OF HIGH-POWER MICROWAVE SOURCES

	当前水平 1	本世纪末水平 2
峰值功率 3	切伦科夫产生器和相对论速调管超过 10GW 大多数微波源超过 1GW 4	对于线性射束器件可达 100GW 5
6 平均功率	在峰值功率为 1GW 时低于 10kW 7	在峰值功率为 1GW 时超过 100kW 接近 1MW 8
效 率 9	功率效率为 10%—20% 能量效率低于 10% 10	能量效率为 50% 11
脉冲宽度 12	大多数微波源约为 100ns 有几种微波源约为 1μs 13	大多数微波源大于 1μs 有几种微波源达到 10μs 14
单脉冲能量 15	一般低于 100J 切伦科夫产生器和相对论速调管高于 1kJ 16	几种微波源达到 10kJ 17

KEY: 1 - present level 2 - potential level by end of this century 3 - peak power 4 - Cerenkov generator and relativistic velocity-regulation tube exceed 10GW. Most microwave sources exceed 1GW 5 - linear beam transmitter can reach 100GW 6 - average power 7 - lower than 10kW when peak power is 1GW 8 - over 100kW, nearly 1MW when peak power is 1GW 9 - efficiency 10 - power efficiency 10 to 20%; energy efficiency<10% 11 - energy efficiency 50% 12 - pulse duration 13 - most microwave sources approximately 100ns. Some microwave sources approximately 1mus 14 - most microwave sources>1mus. Some microwave sources reach 10mus 15 - monopulse energy 16 - generally less than 100J. Cerenkov generator and relativistic velocity-regulation tube>1kJ 17 - some microwave sources reach 10kJ

d) The natural enemy of radar is the antiradiation missile. Typically, a high-power microwave weapon transmitting microwave beams may suffer from an attack by antiradiation missiles. There

are some measures that can be used to handle antiradiation missiles, such as jamming, deception, protective measures as well as enhancing self-mobility, etc. But these measures are all passive. An active measure is detecting and destroying antiradiation missile as early as possible.

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